

LA-UR-04-2115

Approved for public release;
distribution is unlimited.

Title:

***Temperature Dependence of the Spectral
Response of a St. Gobain Thallium-Activated
Cesium Iodide PIN Photodiode Array***

Author(s):

*Mohini Rawool-Sullivan (N-2), William Baird (N-2), Andrew Hoover
(ISR-1), R. Marc Kippen (ISR-1), and John Sullivan (P-25)*

Submitted to:

Department of Energy (DOE)



Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Temperature Dependence of the Spectral Response of a St. Gobain Thallium-Activated Cesium Iodide PIN Photodiode Array

Mohini Rawool-Sullivan (N-2), William Baird (N-2), Andrew Hoover (ISR-1), R. Marc Kippen (ISR-1), and John Sullivan (P-25)

Los Alamos National Laboratory

Los Alamos, NM 87545

LA-UR-04-2115

Abstract

For the position-sensitive absorbing detection plane of the Los Alamos National Laboratory prototype Compton imager, we have elected to use an array of 42 thallium-activated cesium iodide scintillators. In the array, each scintillator is individually glued to a silicon PIN photodiode (CsI(Tl)/PIN). The purpose of this plane is to stop the Compton-scattered gamma ray and measure its energy and the position of the interaction. This progress report describes the temperature dependence of the spectra obtained using the individual elements of this array.

Introduction

Gamma rays can be either directly detected via high-Z materials such as HPGe, CdZnTe, CdTe, and HgI₂ crystals, or they can be indirectly detected using scintillators such as NaI(Tl) and CsI(Tl). Direct detection offers good resolution, but low efficiency. In indirect detection (such as in scintillators), the gamma-ray energy is converted into light photons. The light output can be read out using photomultiplier tubes (PMT) or silicon photodiodes, such as PIN or avalanche photodiodes (APDs). Photomultiplier tubes are bulky, sensitive to magnetic fields, and use a high-voltage power supply. Avalanche photodiodes also require a high-voltage power supply. In addition, the output from APDs is very sensitive to temperature variations. On the other hand, PIN silicon photodiodes can be used without a high-voltage power supply. As compared to APDs and PMTs, PIN silicon photodiodes have a lower sensitivity to magnetic fields and temperature variations. The main drawback of PIN silicon photodiodes is that, unlike APDs and PMTs, they do not have internal signal amplification. Thus with PIN silicon photodiodes, it is often necessary to use associated electronics that will keep electronic noise to a minimum, because it is higher than the statistical noise at lower energies.

CsI(Tl) has an emission spectrum around 565 nm, which coincides with the absorption spectrum of silicon. The density of CsI(Tl) is 4.53 g/cm³. The radiation length of CsI(Tl) at 662 keV is 1.85 cm, and its effective atomic number is 54. The measured scintillation yield of CsI(Tl) is 64,800 photons/MeV for gamma rays at room temperature.¹ The refractive index of CsI(Tl) is 1.80 in the visible range.

¹ J. D. Valentine, D. K. Wehe, G. F. Knoll, and C. E. Moss, Conf. Recors 1991 IEEE Nucl. Sci. Symp. 1 (1991), p. 176.

The CsI/PIN Diode Detector Array

The CsI/PIN diode elements are arranged into a six- by seven-element array. Each CsI crystal is $1.44\text{ cm} \times 1.25\text{ cm} \times 1.0\text{ cm}$ in size. Each crystal has an attached PIN diode (S3590-1)² and an H4083³ preamplifier (which we will refer to as a preamp). The crystals, photodiodes, and preamplifiers are housed inside an aluminum box. Figure 1 shows a photograph of the front of the array. The photodiodes are operated with a bias of +40 V. The signals from each crystal are carried over a 15-ft LEMO cable to a patch panel. From the patch panel, the signals are fed through an ORTEC amplifier and an ADC module. The digitized values are read out by a computer over an Ethernet connection.

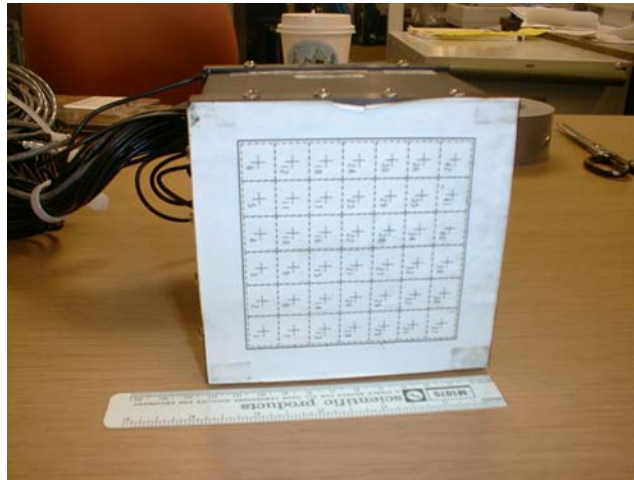


Figure 1: Photograph of the CsI/PIN diode array.

Temperature Behavior of a General CsI(Tl)/PIN Array

It is important to understand the temperature behavior of the individual elements of the CsI(Tl)/PIN array for constructing good images. The temperature dependence of these detectors mainly comes from the thermally excited dark current present in silicon PIN photodiodes at room temperature. Dark current limits the achievable energy resolution. In addition, the dark current increases with a rise in the ambient temperature. The temperature dependence of various detector parameters for CsI(Tl) crystals was measured.⁴ The scintillation yield of CsI(Tl) was observed to be only slightly temperature dependent between -30 and $+50\text{ }^{\circ}\text{C}$, peaking at about $-30\text{ }^{\circ}\text{C}$ (about 6% above room temperature yield) and monotonically decreasing above and below this temperature. On

² http://usa.hamamatsu.com/hcpdf/catsandguides/Si_photodiode.pdf.

³ http://usa.hamamatsu.com/hcpdf/parts_H/H4083.pdf.

⁴ J. D. Valentine, W. W. Moses, S. E. Derenzo, D. K. Wehe, and G. F. Knoll, "Temperature dependence of CsI(Tl) gamma-ray excited scintillator characteristics." NIM A325 (1993), 147–157.

the other hand, the two primary decay-time constants of CsI(Tl) increase exponentially with a decrease in temperature. Thermoluminescence emissions were observed to have peak yields at -90 , -65 , -40 , $+20$, and possibly -55 °C. Thermoluminescence and the decay-time constant dependence for CsI(Tl) work together to give a worse signal-to-noise ratio at lower temperatures, even though the PIN photodiode performance gets better at lower temperatures. Thus, it is reasonable to operate the array at the room temperature. As long as the temperature remains constant, the performance of the array should be consistent.

Temperature Behavior of St. Gobain CsI(Tl)/PIN Array

Once the bias was applied to the preamplifier cards of the St. Gobain array and to the PIN diodes, the temperature inside the box rose quickly. The bias applied to the preamp cards was ± 12 V. This bias was specified by St. Gobain. In one measurement, the temperature on the outside of the box rose from room temperature (approximately 85 °F) to 100 °F within 30 minutes. With the increase in temperature, the photopeak width got wider. At much higher temperatures (after we had left the voltage on for a few days), the photopeaks completely vanished. Turning off the voltages for an hour or so generally restored the temperature and the performance of the detector back to ‘normal’. With the rise in the temperature the peak at the lower end moved to a higher channel and got sharper. Figure 2 shows a plot of 661.6 keV spectra at 85 °F (29.44 °C - solid blue line) and 128.1 °F (53.39 °C solid red line). To measure the temperature, we placed a temperature probe just inside the box via the small holes through which the LEMO cables exit. The data shown in Figure 2 were taken using crystal #22. The source was placed 12.7 cm (5 in.) away from the crystal. To keep the temperature rise in check, we installed a small fan that blew air onto the back of the CsI array box. This lowered the rate of temperature increase. The fan was in use when the data was taken on crystal #22. The data shown in Figure 3 was taken on crystal #1.

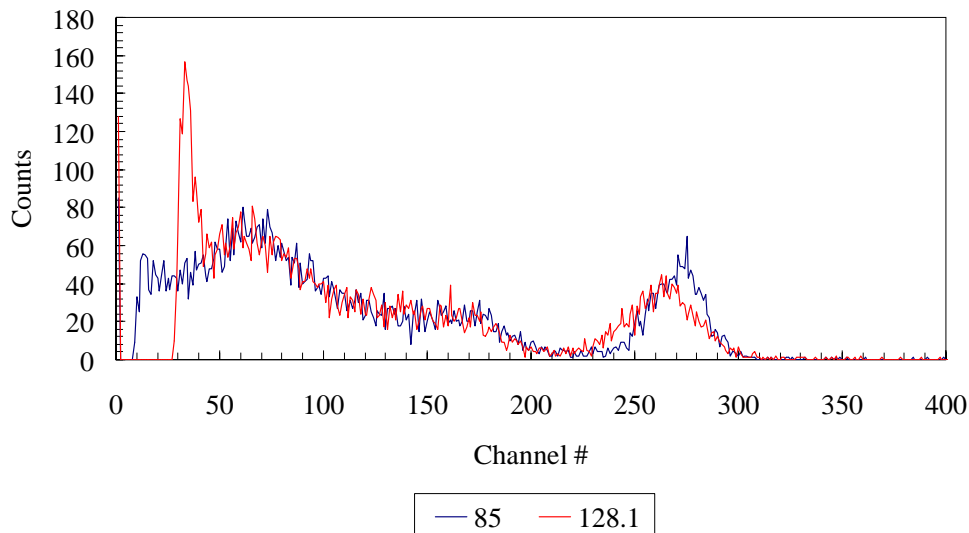


Figure 2: Variation in the Cs-137 spectrum as a function of temperature (given in °F) for crystal #22.

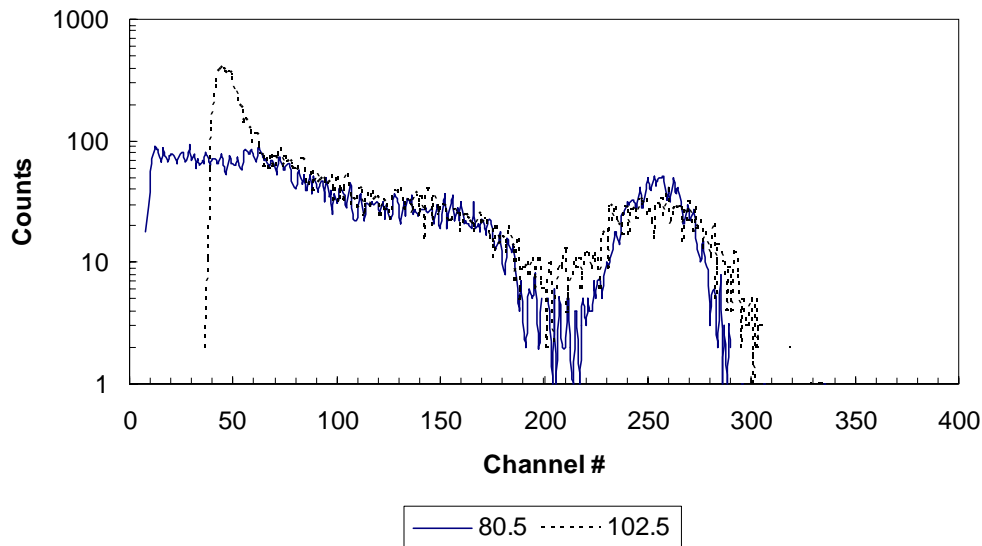


Figure 3: Variation in the Cs-137 spectrum as a function of temperature given in °F for crystal #1.

The type of changes observed in Figs. 2 and 3 will definitely degrade the overall performance of the CsI(Tl)/PIN array, and therefore the performance of the Compton gamma-ray imager that we are trying to construct. In the long run, we hope to design a preamp board in-house that will have low power consumption and better performance. The design of the new board will not be completed until FY05. We have borrowed from St. Gobain a CsI(Tl)/PIN test module with a preamp; the test module is identical in every respect to the individual elements in the array. This test module is being used to design the new preamp board.

For this year's data acquisition, we will have to use the St. Gobain preamps. To lower the power consumption of these preamps, William Baird proposed a reduction in the preamp bias voltage. As mentioned earlier in this paper, the St. Gobain preamp uses ± 12 V for its bias voltage. Using the test module, we measured that the +12-V bias on the preamp draws 18 mA current, or 0.22 W of power. The -12-V bias uses 13 mA (or 0.16 W) of power. Assuming that the module we tested had 'average' performance, we can conclude that the 42 units in the entire array would dissipate a total of 15.8 watts.

The bias voltage was then lowered to ± 6 V.⁵ The +6-V bias consumes 10 mA, and the -6-V bias consumes 8 mA. The total dissipation for 42 detectors is then 4.5 watts. Thus, if the bias voltage is ± 6 V (instead of ± 12 V), the heating of the CsI array will be considerably lower. Still, it is necessary to prove that reducing the preamp voltage does not adversely affect the performance of the detector system. Our initial measurements used the test module. The +40-V bias was used on the PIN diodes in all measurements. The pulse shape did not appear to change as we lowered the preamp voltage. The pulse shape is shown in comparison with Am-241 in Figure 4. A similar plot of the pulse shape

⁵ This value was picked at random for initial testing of the proposed concept.

with a Cs-137 source is shown in Figure 5. For both sources, the pulse shapes and amplitudes are similar with 6- and 12-V preamp voltage.

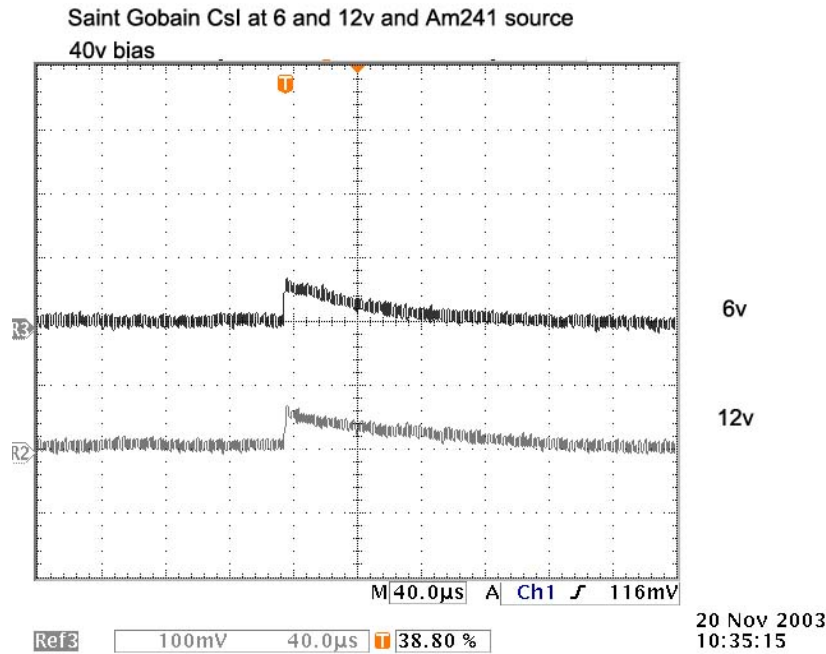


Figure 4: Preamp pulse for 6- and 12-V preamp voltage using an Am-241 source. Note that the Am-241 source has a 59.54 keV gamma ray with a branching ratio of 35.7%. There are several other gamma rays at lower branching ratios.

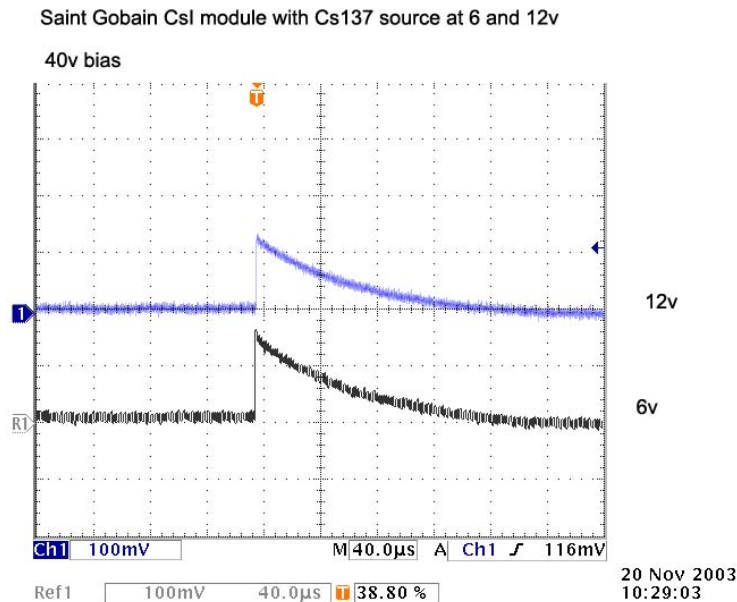


Figure 5: Preamp pulse for 6- and 12-V preamp voltage using a Cs-137 source.

We measured temperature inside the array box using ± 5 V and ± 12 V for preamp voltage. The PIN diode bias was +40 V. The plot is shown in Figure 6. The data

represented by the red line were taken with 12-V preamp voltage. The blue data set and black data set were measured with 5-V preamp voltage. The rate of change of temperature varies depending on exactly where the probe is put inside the box.

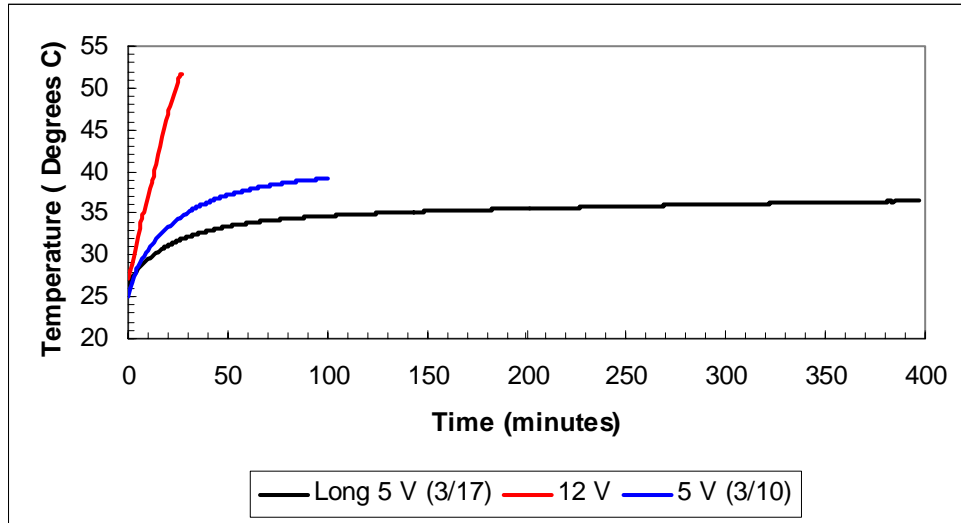


Figure 6: The temperature variations within CsI array box as a function of preamp voltage and location of the probe.

Spectral Response as a Function of Preamp voltage

To study the effect of variation in preamp voltage on the measured spectra, we varied the preamp voltage between 3.5 V and 9 V. We collected spectra using an AmpTek 8000A MCA (multichannel analyzer). The PIN diode bias was set at 40 V. The source-to-detector distance was kept at 25 cm. The same Cs-137 source was used for all of the measurements tabulated in Table 1. The preamp quit working at a preamp voltage of approximately 3.2 V. The spectra (black line) and fits to the 661.66 keV photopeak (red line) are shown in Figures 7–13 for individual preamp voltage measurements. Figure 14 shows data for various preamp voltages plotted on a single graph.

Table 1: The 661.66 keV Gamma-Ray Spectrum Characteristics as a Function of Preamp voltage

Preamp voltage (V)	Current (mA)	Mean (ADC channel)	Sigma (channels)	Sigma/Mean	Total counts in the spectrum
3.5	7.12	3120	127.2	0.0408	1147413
4	7.85	3209	126.9	0.0395	1142787
5	9.07	3254	127.4	0.0392	1134364
6	10.37	3282	129.1	0.0393	1121551
7	11.73	3299	130.4	0.0395	1121226
8	13.13	3290	130.8	0.0398	1117823
9	14.53	3307	131.8	0.0399	1101565

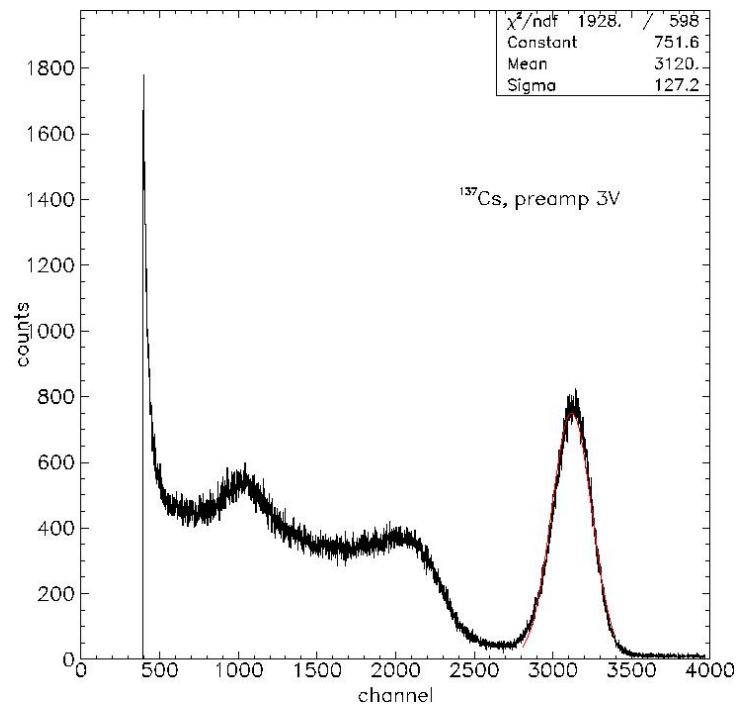


Figure 7: Fit (red line) and data (black line) at 3.5 V.

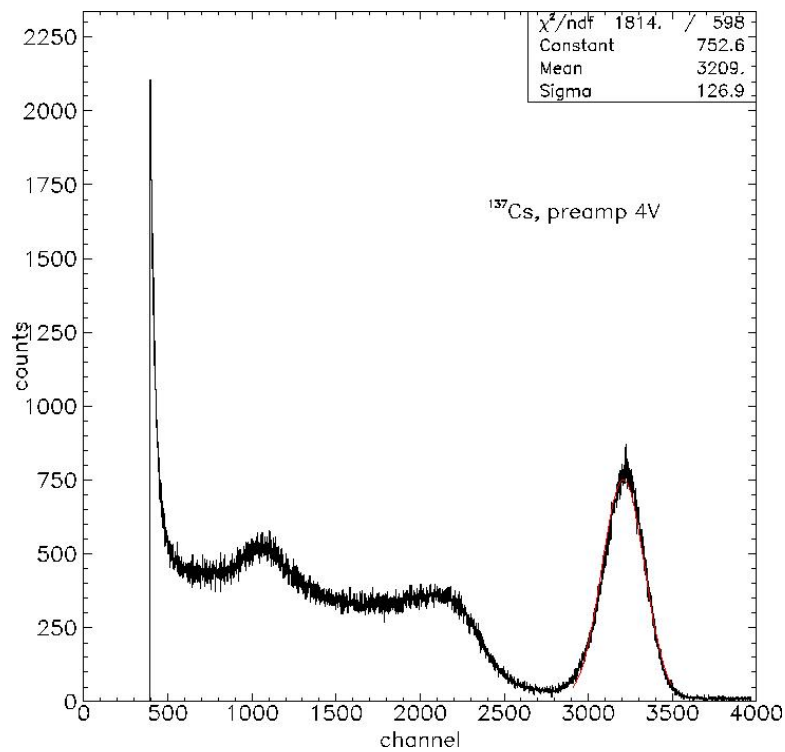


Figure 8: Fit (red line) and data (black line) at 4 V.

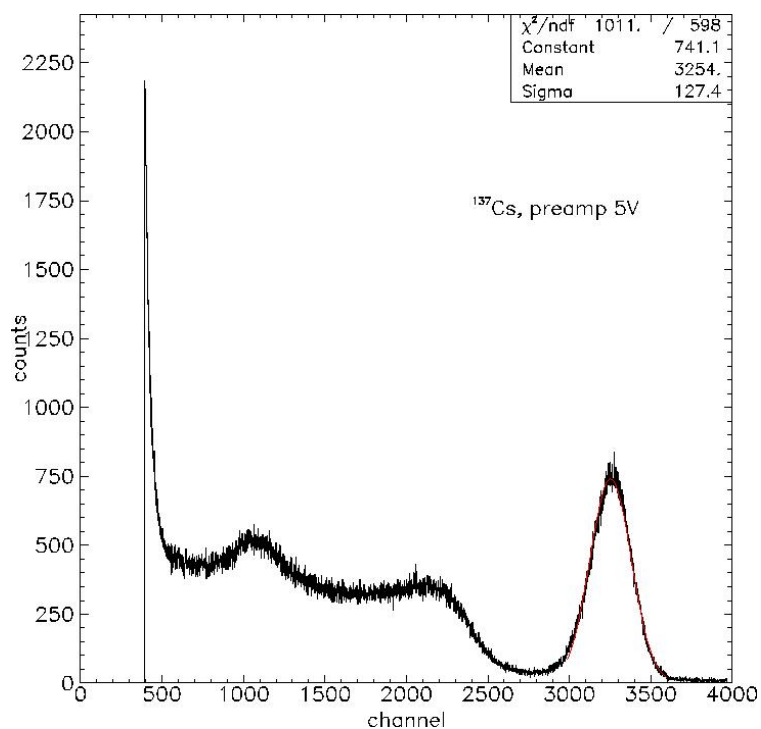


Figure 9: Fit (red line) and data (black line) at 5 V.

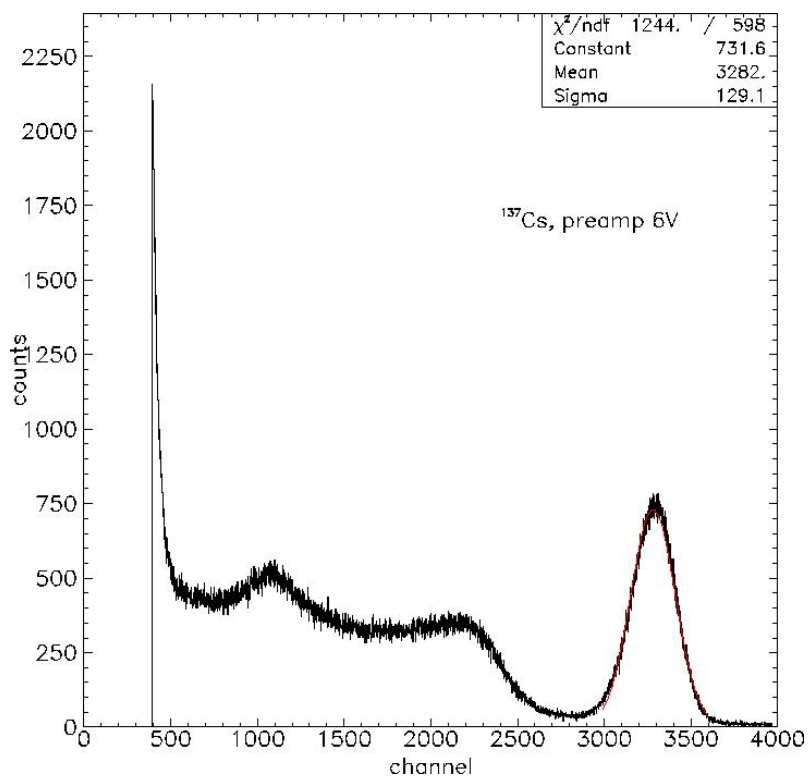


Figure 10: Fit (red line) and data (black line) at 6 V.

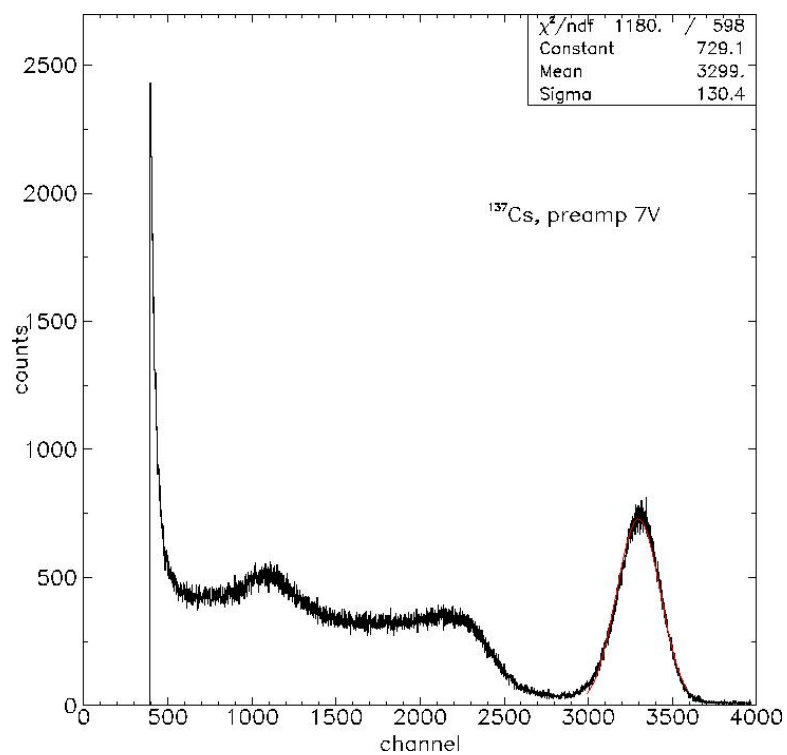


Figure 11: Fit (red line) and data (black line) at 7 V.

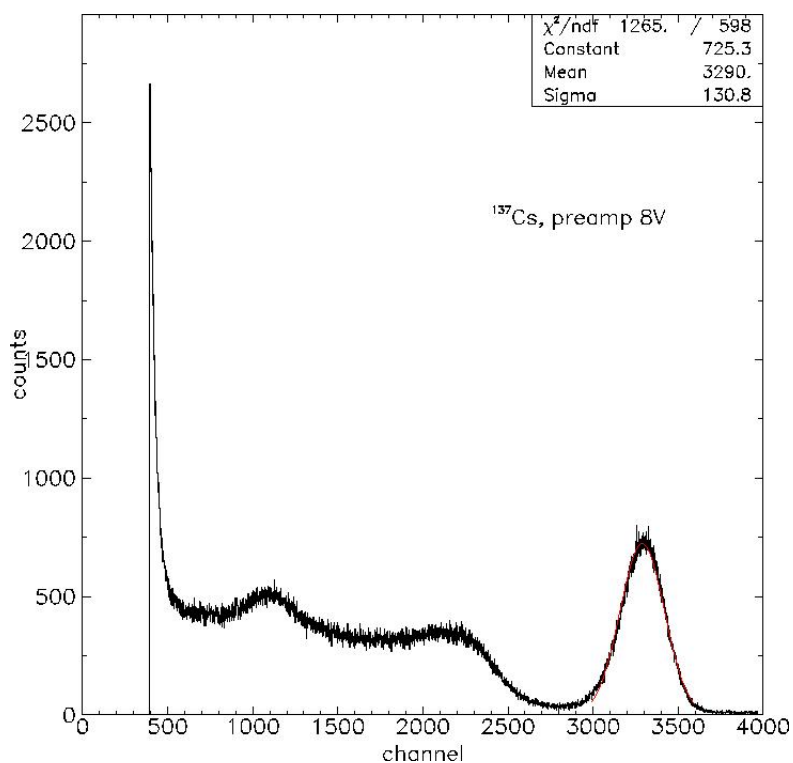


Figure 12: Fit (red line) and data (black line) at 8 V.

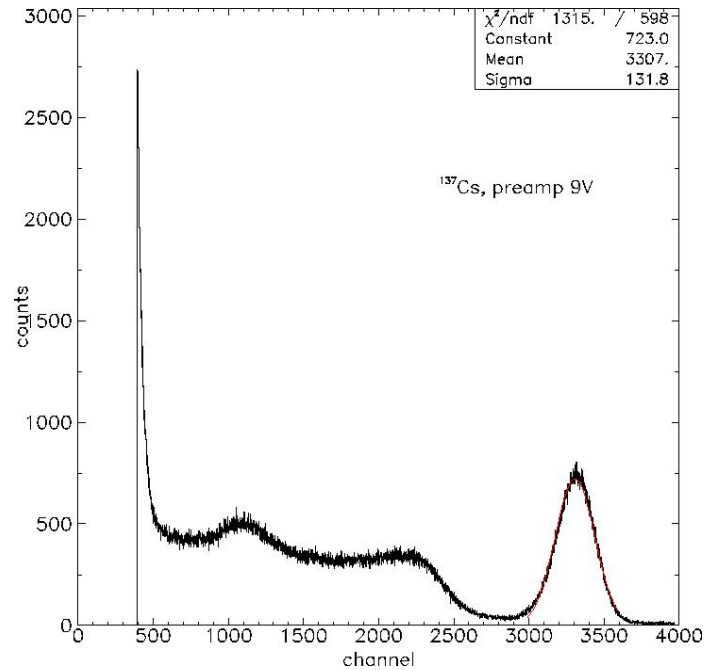


Figure 13: Fit (red line) and data (black line) at 9 V.

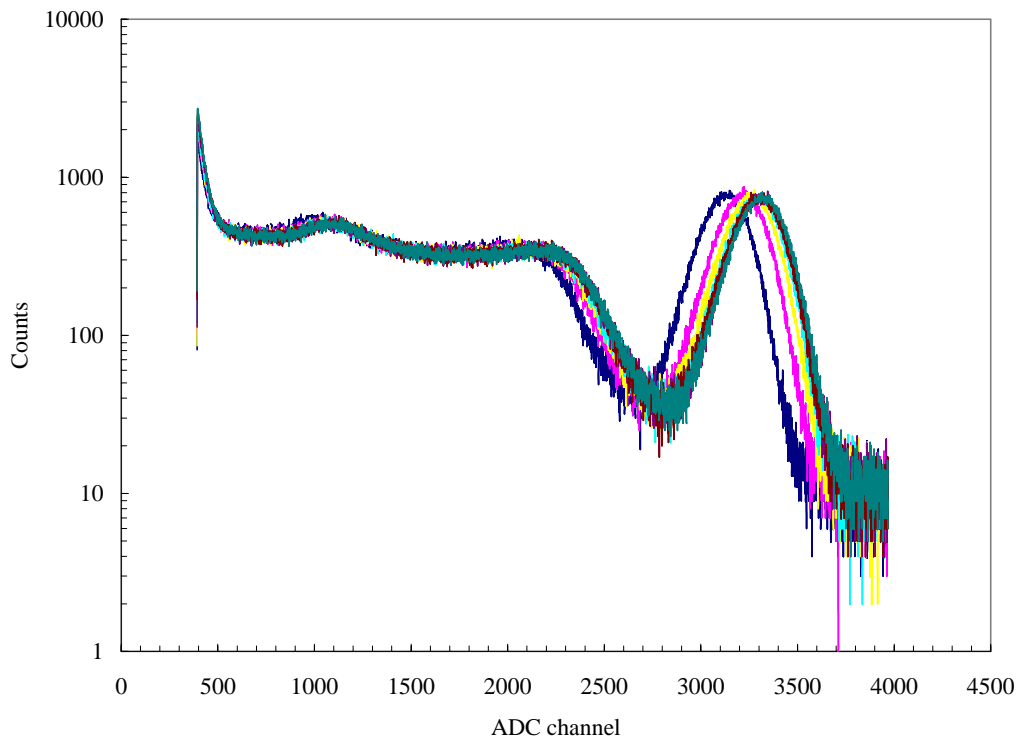


Figure 14: Spectra from CsI/PIN detector at various preamp voltages.

Data in Fig. 14 show that reducing the preamp bias lowers the overall system gain. This is about a 10% effect in going from 12V to 5V. This small shift in gain will not significantly affect the capability of the Compton imager. In Table 1, we can see that the

minimum sigma/mean parameter occurs at 5 V of preamp voltage. It is our conclusion that lowering the preamp voltage to 5 V certainly does not degrade the performance of the CsI(Tl)/PIN detectors, but does reduce the temperature of the system.

Response of CsI/PIN Test Module to Various Gamma-Ray Energies with Preamp voltage at 5 V

To study the response of the test module at 5 V of preamp voltage, the following sources were used: Ba-133, Co-57, Co-60, Na-22, and Ho-166m. Table 2 summarizes the sources used along with the corresponding activity and the date of the activity measurements. Table 3 tabulates the gamma-ray energies that are used in plotting the linearity curve and the corresponding resolution, peak areas, and mean and sigma of the peak in terms of the channel numbers. The Ba-133 peaks are not included in Table 3 because Ba-133 has multiple overlapping photopeaks that are hard to distinguish. Each spectrum was collected at a source-to-detector distance of 25 cm. The PIN photodiode bias was set at +40 V. An appropriate threshold was used to eliminate the noise in the lower ADC channels. Each spectrum was collected for 1,800 seconds of live time. For each source spectrum, the data in the region of the photopeaks was fitted with a Gaussian function. The obtained energy spectra (black line) and some of the resulting fits (red lines) are shown in Figures 15–19. These data were taken with an AmpTek 8,000A MCA.

Table 2: Activity of the Gamma-Ray Sources

Gamma source	Activity (μCi)	Date of the activity measurement
Ba-133	1.62	1/9/02
Co-60	5.7	1/9/02
Co-57	344.6	2/1/03
Cs-137	5.9	1/9/02
Ho-166m	9.8	1/9/02
Na-22	0.4	10/18/01

Table 3: Gamma-Ray Energies and the Corresponding Fit Parameters

Gamma-ray source	Energy (keV)	Branching ratio	Mean (channel #)	Sigma (channel #)	Peak area (counts)
Co-57	123.70	96.40	293.70	60.01	2081218.65
Ho-166m	184.41	74.66	450.00	66.42	77092.17
Ho-166m	280.41	30.40	668.65	77.36	22293.82
Na-22	511.00		1214.30	65.86	585.05
Ho-166m	810.23	63.99	1904.90	70.85	2386.74
Co-60	1173.24	99.90	2753.20	61.88	859.44
Co-60	1332.50	99.98	3123.00	72.05	608.89

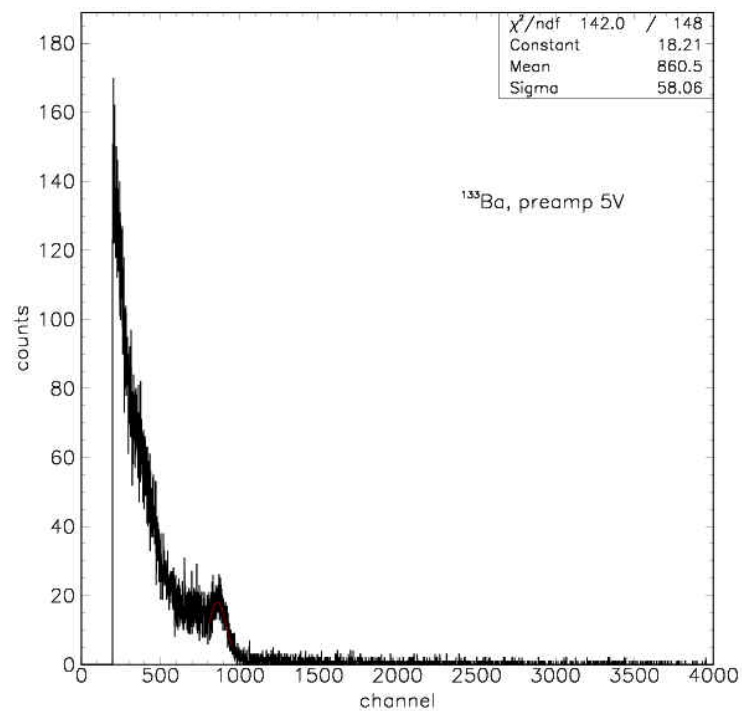


Figure 15: Ba-133 spectrum.

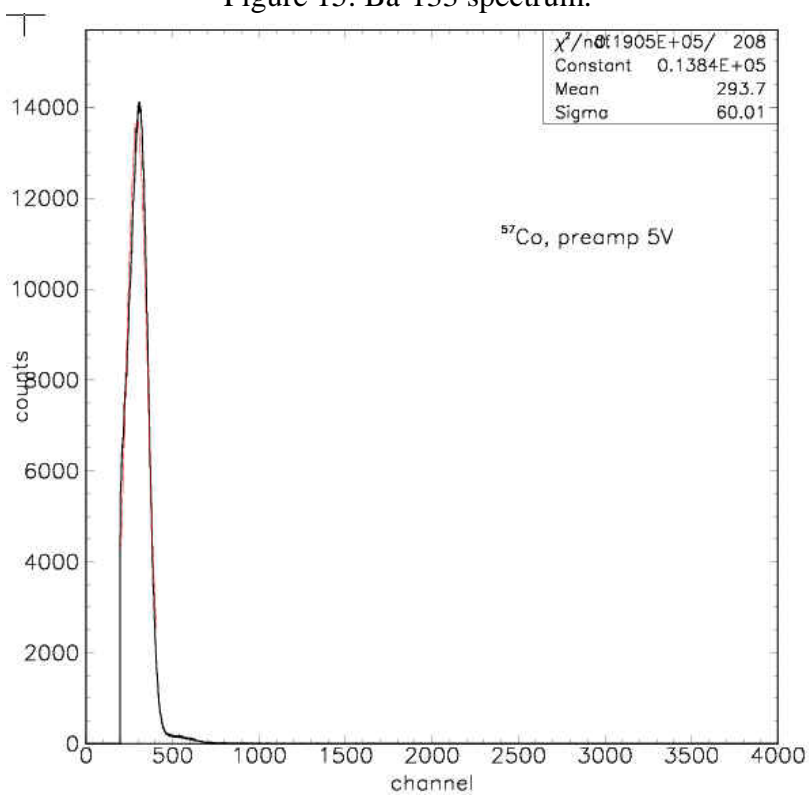


Figure 16: Co-57 spectrum.

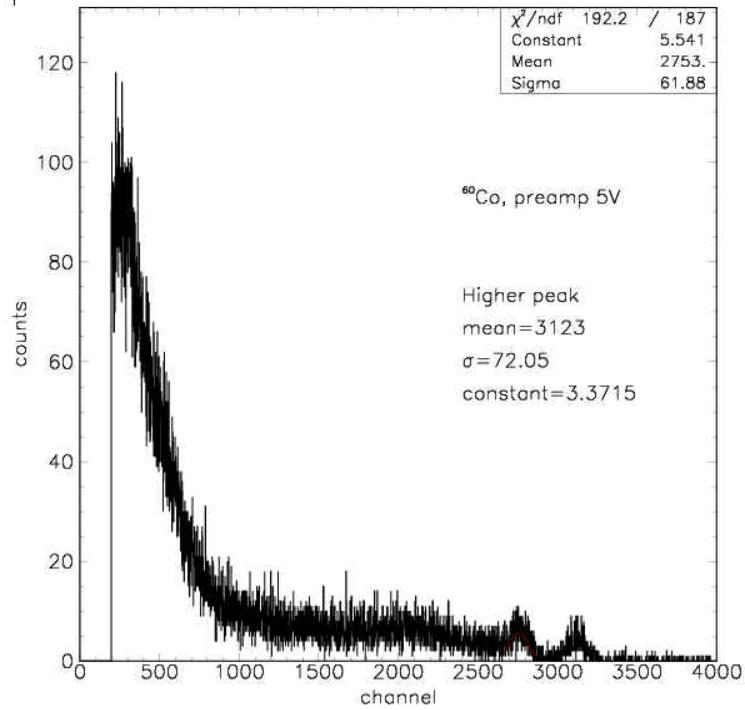


Figure 17: Co-60 spectrum.

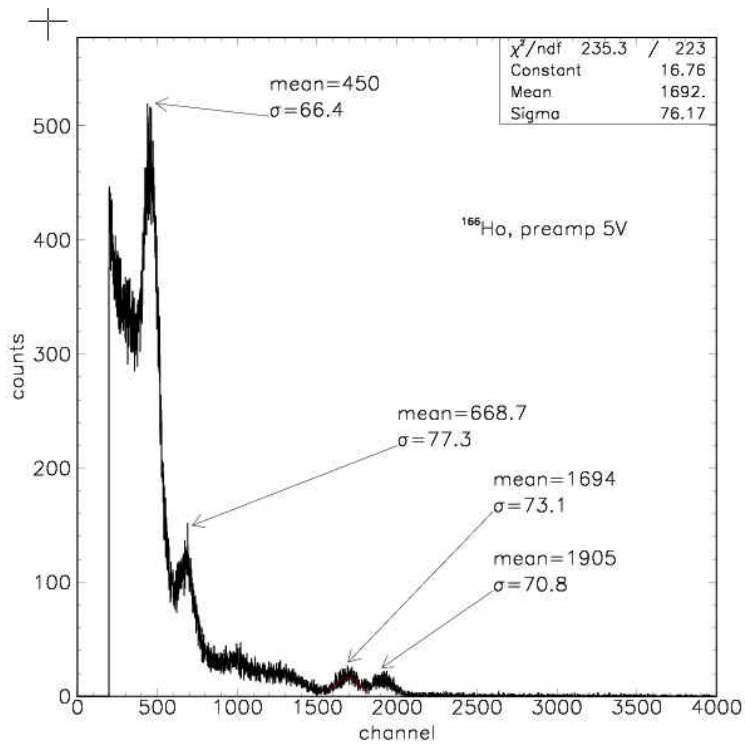


Figure 18: Ho-166m spectrum.

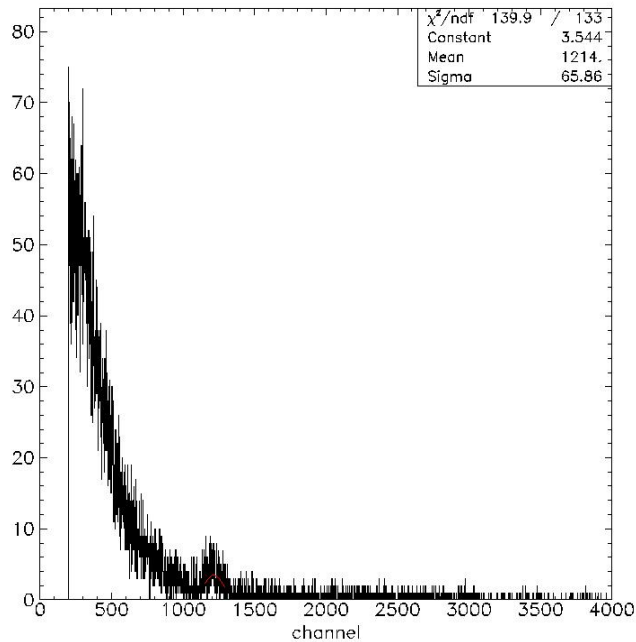


Figure 19: Na-22 spectrum.

The calibration curve for the CsI(Tl) test module using the data in Table 2 is shown in Figure 20. The red line indicates the fit to the data. The slope of this line is 2.3346 channels/keV, and the y intercept is at 14.22 channels.

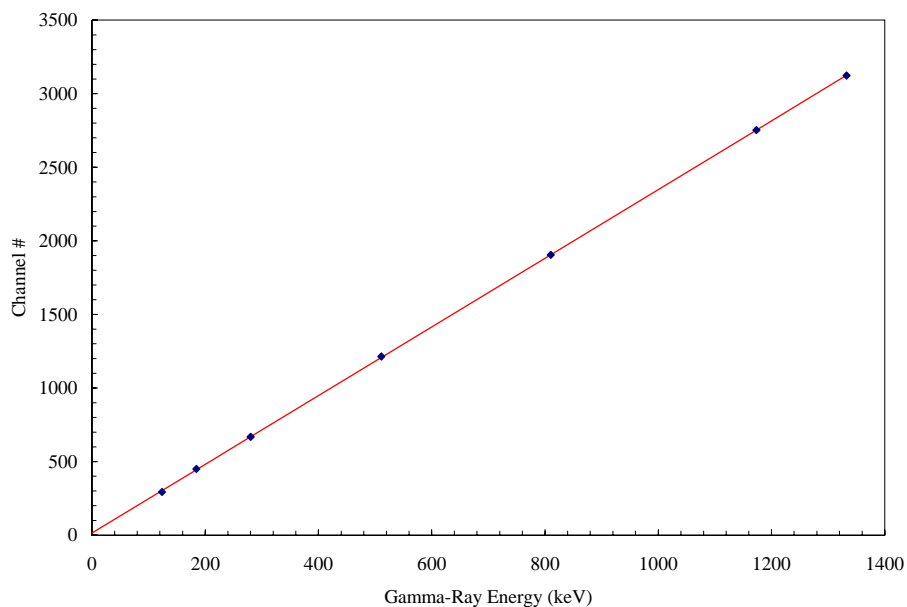


Figure 20: Gamma-ray energy versus ADC channel number. Blue diamonds indicate data points, and the red line indicates the fit to the data.

Evaluation of the St. Gobain Array with ± 5 -V Preamp voltage

Next, we studied the effect of lowering the preamp voltage to ± 5 V on the 42-element array of CsI(Tl)/PIN diode detectors (the measurements in the previous section were made with the test module). These results were then compared with the results measured earlier with the same array. Figure 21 shows the comparison between data sets with ± 5 -V and ± 12 -V biases on crystal #22 using the same Cs-137 source. Similar comparisons for crystal #22 with a Co-60 source and Na-22 source are shown in Figures 22 and 23, respectively. A pulse shaping time of 2 μ s was used in all measurements. The source-to-detector distance was kept at 5 in. (12.7 cm). The Si PIN bias was set at +40 V. These two data sets were taken one year apart from each other. Thus, although the same sources were used, the strength of the source varied depending on the half-life of the source.

Figure 21 shows the Cs-137 spectra for two preamp voltage settings. The source activity was 8.14 μ Ci for the ± 12 -V spectrum and 7.98 μ Ci for the ± 6 -V spectrum. The peak centroid for Cs-137 shifted to the lower channel. This shift may be due to the differing temperatures at which these two data sets were taken. Figure 22 shows Co-60 spectra for two preamp voltage settings. The source activity was 1.92 μ Ci for the ± 12 -V spectrum and 1.71 μ Ci for the ± 6 -V spectrum. Figure 23 shows Na-22 spectra for two preamp voltage settings. The source activity was 0.26 μ Ci for the ± 12 -V spectrum and 0.21 μ Ci for the ± 6 -V spectrum. This partly explains the smaller number of counts in the red spectrum (5 V) compared to blue spectrum (12 V) in all three figures. For all sources, the data with a lower preamp voltage have better resolution than do the data with a higher preamp voltage.

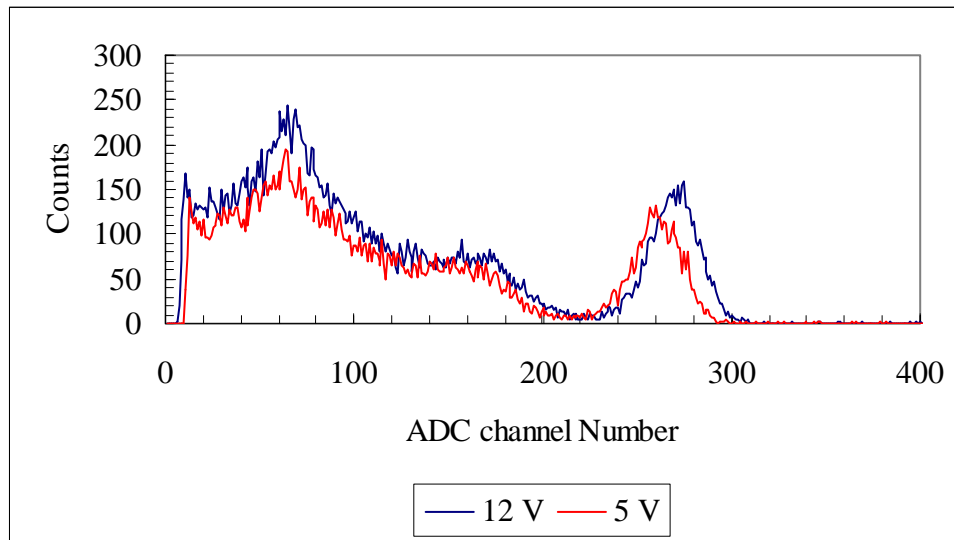


Figure 21: This data was taken using crystal #22 and a Cs-137 source. The blue line indicates the spectrum measured with ± 12 -V preamp voltage, and the red line indicates the spectrum measured with ± 5 -V preamp voltage. A live time of 300 sec was used in collecting the data.

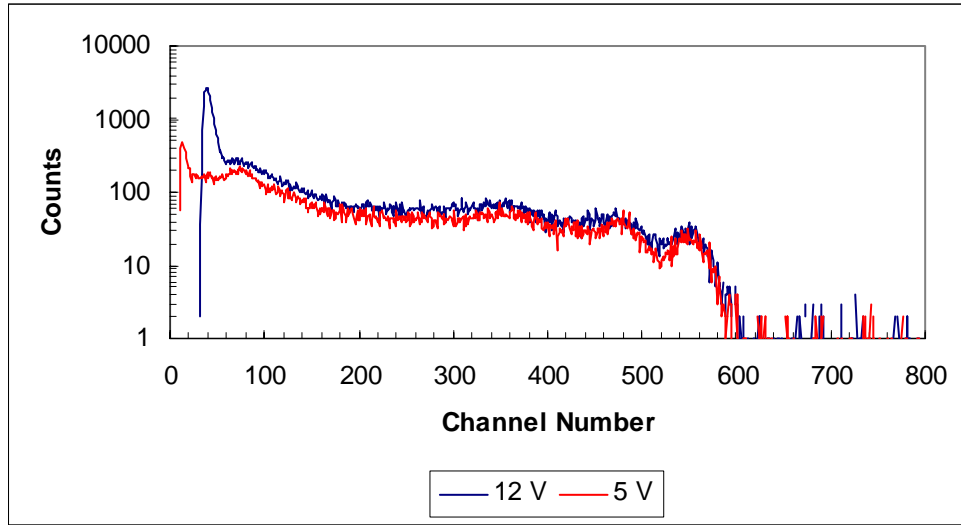


Figure 22: This data was taken using crystal # 22 and a Co-60 source. The blue line indicates the spectrum measured with ± 12 -V preamp voltage, and the red line indicates the spectrum measured with ± 5 -V preamp voltage. A live time of 1,200 sec was used in measuring both data sets.

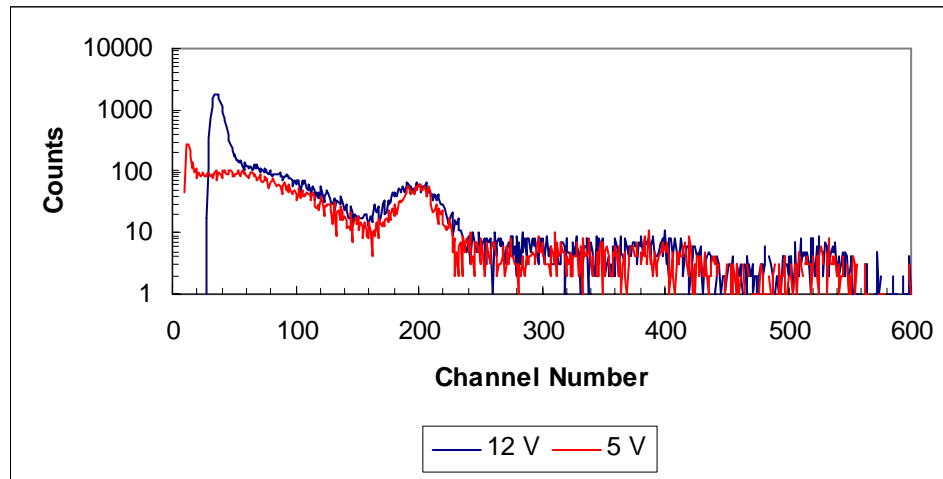


Figure 23: This data was taken using crystal #22 and a Na-22 source. The blue line indicates the spectrum measured with ± 12 -V preamp voltage, and the red square data set indicates the spectrum measured with ± 5 -V preamp voltage. A live time of 1,800 sec was used in measuring the red data set. The live time was set at 1,200 sec for the blue data set.

Conclusions

While conducting laboratory tests, we observed that as the preamp voltage of ± 12 V was applied along with +40-V bias to the PIN diodes, the temperature of the entire array rose steadily. This also resulted in the degradation of the performance of the array elements. As a solution, the preamp voltage was lowered to ± 5 V. This leveled the temperature rise of the array after initial rise. The performance of detector elements seems to be better

with the lower preamp voltage. We found that reducing the preamp bias lowers the overall system gain. This is about a 10% effect in going from 12V to 5V. This small shift in gain will not significantly affect the capability of the Compton imager.